

SYSTEM FOR CONFIGURING AUDIO SYSTEM

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BACKGROUND OF THE INVENTION

1. Related Applications.

10 [001] This application claims priority to U.S. Provisional Application Serial No. 60/492,688 entitled "In-Room Low Frequency Optimization" filed on August 4, 2003, and is incorporated by reference in its entirety. This application claims priority to U.S. Provisional Application Serial No. _____ entitled "In-Room Low Frequency Optimization," Attorney Reference Number 11336/643 P03059USV1, filed on October 9, 2003, and is incorporated by reference in its entirety.

15 [002] The following copending and commonly assigned U.S. patent applications have been filed on the same day as this application. All of these applications relate to and further describe other aspects of this invention and are incorporated by reference in their entirety.

20 [003] U.S. Patent Application Serial Number _____, entitled "Statistical Analysis of Potential Audio System Configurations," Attorney Reference Number 11336/433 P03059US, filed on October 10, 2003, and now U.S. Patent Number _____.

[004] U.S. Patent Application Serial Number _____, entitled "System for Selecting Correction Factors for an Audio System," Attorney Reference Number 11336/434 P03060US, filed on October 10, 2003, and now U.S. Patent Number _____.

25 [005] U.S. Patent Application Serial Number _____, entitled "System for Selecting Speaker Locations in an Audio System," Attorney Reference Number 11336/435 P03061US, filed on October 10, 2003, and now U.S. Patent Number _____.

2. Technical Field.

[006] This invention generally relates to improving sound system performance in a given space. More particularly, the invention relates to improving the frequency response performance for one or more listening positions in a given area thus providing a more enjoyable listening experience.

3. Related Art.

[007] Sound systems typically include loudspeakers that transform electrical signals into acoustic signals. The loudspeakers may include one or more transducers that produce a range of acoustic signals, such as high, mid and low-frequency signals. One type of loudspeaker is a subwoofer that may include a low frequency transducer to produce low-frequency signals.

[008] The sound systems may generate the acoustic signals in a variety of listening environments. Examples of listening environments include, but are not limited to, home listening rooms, home theaters, movie theaters, concert halls, vehicle interiors, recording studios, and the like. Typically, a listening environment includes single or multiple listening positions for a person or persons to hear the acoustic signals generated by the loudspeakers. The listening position may be a seated position, such as a section of a couch in a home theater environment, or a standing position, such as a spot where a conductor may stand in a concert hall.

[009] The listening environment may affect the acoustic signals, including the low, mid, and/or high frequency signals at the listening positions. Depending on where a listener is positioned in a room, the loudness of the sound can vary for different tones. This may especially be true for low-frequencies in smaller domestic-sized rooms because the loudness (measured by amplitude) of a particular tone or frequency may be artificially increased or decreased. Low frequencies may be important to the enjoyment of music, movies, and most other forms of audio entertainment. In the home theater example, the room boundaries, including the walls, draperies, furniture, furnishings, and the like may affect the acoustic signals as they travel from the loudspeakers to the listening positions.

[010] The acoustic signals received at the listening positions may be measured. One measure of the acoustical signals is a transfer function that may measure aspects of the acoustical signals including the amplitude and/or phase at a single frequency, a discrete

number of frequencies, or a range of frequencies. The transfer function may measure frequencies in various ranges.

[011] The amplitude of the transfer function indicates the loudness of a sound. Generally, the amplitude of a single frequency or a range of frequencies is measured in
5 decibels (dB). Amplitude deviations may be expressed as positive or negative decibel values in relation to a designated target value. When amplitude deviations are considered at more than one frequency, the target curve may be flat or of any shape. An amplitude response is a measurement of the amplitude deviation at one or more frequencies from the target value at those frequencies. The closer the amplitude values measured at a listening position
10 correspond to the target values, the better the amplitude response. Deviations from the target reflect changes that occur in the acoustic signal as it interacts with room boundaries. Peaks represent an increased amplitude deviation from the target, while dips represent a decreased amplitude deviation from the target.

[012] These deviations in the amplitude response may depend on the frequency of
15 the acoustic signal reproduced at the subwoofer, the subwoofer location, and the listener position. A listener may not hear low-frequencies as they were recorded on the recording medium, such as a soundtrack or movie, but instead as they were distorted by the room boundaries. Thus, the room can change the acoustic signal that was reproduced by the subwoofer and adversely affect the frequency response performance, including the low-
20 frequency performance, of the sound system.

[013] Many techniques attempt to reduce or remove amplitude deviations at a single listening position. One such technique comprises global equalization, which applies filters equally to all subwoofers in the system. Generally, the amplitude is measured at multiple frequencies at a single position in the room. For example, an amplitude measurement may be
25 taken at 25, 45, 65, and 80 Hz to give an amplitude deviation for each measured frequency. Global equalization may comprise applying filters at each of the subwoofers to reduce a +10 dB deviation at 65 Hz. Global equalization may thus reduce amplitude deviations by either reducing the amplitude of the frequency range having positive deviations from the target or boosting the output of the subwoofers at the frequency range having the greatest negative
30 deviation from the target. Global equalization, however, may only correct amplitude deviations at a single listening position.

[014] Another technique which attempts to reduce or remove amplitude deviations is spatial averaging. Spatial averaging, which is a more advanced equalization method, calculates an average amplitude response for multiple listening positions, and then equally implements the equalization for all subwoofers in the system. Spatial averaging, however, only corrects for a single "average listening position" that does not exist in reality. Thus, even when using spatial averaging techniques, some listening positions still have a significantly better low-frequency performance than other positions. Moreover, attempting to equalize for a single location potentially creates problems. While peaks may be reduced at the average listening position, attempting to reduce the dips requires significant additional acoustic output from the subwoofer, thus reducing the maximum acoustic output of the system and potentially creating large peaks in other areas of the room.

[015] Apart from equalization and spatial averaging, prior techniques have attempted to improve the sound quality at a specific listening position using loudspeaker positioning. One technique analyzes standing waves in order to optimize the placement of the loudspeakers in a room. Standing waves may result from the interaction of acoustic signals with the room boundaries, creating modes that have large amplitude deviations in the low-frequency response. Modes that depend only on a single room dimension are called axial modes. Modes that are determined by two room dimensions are called tangential modes and, modes that are the result of all three room dimensions are called oblique modes.

[016] Figure 1 is a pictorial representation of the first four axial modes for a single room dimension for an instant in time. Sound pressure maxima exist at the room boundaries (*i.e.*, the two ends in Figure 1). The point where the sound pressure drops to its minimum value is commonly referred to as a "null." If there is no mode damping at all the sound pressure at the nulls drops to zero. However, in most real rooms the response dip at the nulls are in the -20 dB range. As shown in Figure 1, standing waves may have peaks and dips at different positions throughout the room so that large amplitude deviations may occur depending on where a listener is positioned. Thus, if listener C is positioned in a 30 Hz peak, any 30 Hz frequency produced by the subwoofer will sound much louder than it should. Conversely, if listener D is positioned in a 30 Hz dip, any 30 Hz frequency produced by the subwoofer will sound much softer than it should. Neither corresponds to the acoustic signal reproduced by the subwoofer or previously recorded on the recording medium.

[017] There are several methods to reduce standing waves in a given listening room through positioning of loudspeakers. One method is to locate the subwoofer at the nulls of the standing waves. Specifically, the loudspeaker and a specific listening position may be carefully located within the room so that the transfer function may be made relatively smooth at the specific listening position. A potential loudspeaker-listener location combination is shown in Figure 2 with the first four axial modes along the length of the room. The specific listening position may be located away from the maxima and nulls for the first, second and fourth order modes, while the loudspeaker may be located on the null of the third order mode. As a result, if these are the only resonant modes in the room, this specific listening position should have a relatively smooth transfer function. However, this method merely focuses on a single, specific listening position in order to reduce the effects of standing waves in the listening environment; it does not consider multiple listening positions or a listening area. In practice, the presence of other axial, tangential, and oblique room modes make prediction using this method unreliable.

[018] Another method is to position multiple subwoofers in a "mode canceling" arrangement. By locating multiple loudspeakers symmetrically within the listening room, standing waves may be reduced by exploiting destructive and constructive interference. However, the symmetric "mode canceling" configuration assumes an idealized room (*i.e.*, dimensionally and acoustically symmetric) and does not account for actual room characteristics including variations in shape or furnishings. Moreover, the symmetric positioning of the loudspeakers may not be a realistic or desirable configuration for the particular room setting.

[019] Still another technique to configure the audio system in order to reduce amplitude deviations is using mathematical analysis. One such mathematical analysis simulates standing waves in a room based on room data. For example, room dimensions, such as length, width, and height of a room, are input and the various algorithms predict where to locate a subwoofer based on data input. However, this mathematical method does not account for the acoustical properties of a room's furniture, furnishings, composition, etc. For example, an interior wall having a masonry exterior may behave very differently in an acoustic sense than its wood framed counterpart. Further, this mathematical method cannot effectively compensate for partially enclosed rooms and may become computationally onerous if the room is not rectangular.

[020] Another mathematical method analyzes the transfer functions received at the listening positions and solves for equal transfer functions received at the listening positions. Figure 3 illustrates an example of a multi-subwoofer multi-receiver scenario in a room. Reference I is the signal input to the system. The loudspeaker/room transfer functions from loudspeaker 1 and loudspeaker 2 to two receiver locations in the room are shown as H_{11} through H_{22} , while R_1 and R_2 represent the resulting transfer functions at two receiver locations. Each source has a transmission path to each receiver, resulting in four transfer functions in this example. Assuming the signal sent to each loudspeaker can be electrically modified, represented by M_1 and M_2 , the modified signals may be added. Here, M is a complex modifier that may or may not be frequency dependent. To illustrate the complexity of the mathematical solution, the following equations solve a linear time invariant system in the frequency domain:

$$R_1(f) = IH_{11}(f)M_1(f) + IH_{21}(f)M_2(f) \quad (1)$$

$$R_2(f) = IH_{12}(f)M_1(f) + IH_{22}(f)M_2(f),$$

where all transfer functions and modifiers are understood to be complex. This is recognized as a set of simultaneous linear equations, and can be more compactly represented in matrix form as:

$$\begin{bmatrix} H_{11} & H_{21} \\ H_{12} & H_{22} \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \end{bmatrix}, \quad (2)$$

or simply,

$$HM = R, \quad (3)$$

where the input I has been assumed to be unity.

[021] A typical goal for optimization is to have R equal unity, *i.e.*, the signal at all receivers is identical to each other. R may be viewed as a target function, where R_1 and R_2 are both equal to 1. Solving equation (3) for M (the modifiers for the audio system), $M = H^{-1}$, the inverse of H . Since H is frequency dependent, the solution for M must be calculated at each frequency. The values in H , however, may be such that an inverse may be impossible to calculate or unrealistic to implement (such as unrealistically high gains for some loudspeakers at some frequencies).

[022] As an exact mathematical solution is not always feasible to determine, prior approaches have attempted to determine the best solution calculable, such as the solution with

the smallest error. The error function defines how close is any particular configuration to the desired solution, with the lowest error representing the best solution. However, this mathematical methodology requires a tremendous amount of computational energy, yet only solves for a two-parameter solution. Acoustical problems that examine a greater number of parameters are increasingly difficult to solve.

[023] Therefore, a need exists for a system to accurately determine a configuration for an audio system such that the audio performance for one or more listening positions in a given space is improved.

SUMMARY

[024] This invention is a system for configuring an audio system for a given space. The system may analyze any variable or parameter in the audio system configuration that affects the transfer function at a single listening position or multiple listening positions. Examples of parameters include the position of the loudspeakers, the number of loudspeakers, the type of loudspeakers, the listening positions, non-temporal correction factors (*e.g.*, parametric equalization, frequency independent gain), and temporal correction factors.

[025] The system provides a statistical analysis of predicted transfer functions. The statistical analysis may be used to configure a single or multiple listener audio system, such as to select a value for a parameter or values for parameters in the audio system. Transfer functions, including amplitude and phase, may be measured at a single listening position or multiple listening positions. The transfer functions may comprise raw data measured by placing a loudspeaker at potential loudspeaker locations and by registering the transfer functions at the listening positions using a microphone or other acoustic measuring device. The transfer functions may then be modified using potential configurations of the audio system, such as potential parameter values. Examples of potential parameter values include potential positions for the loudspeakers, potential numbers of loudspeakers, potential types of loudspeakers, and/or potential values for correction factors. The modified transfer functions may represent predicted transfer functions for the potential configurations. At least a portion of the predicted transfer functions, such as the amplitude or the amplitude within a particular frequency band, may then be statistically analyzed for the single listening position or the multiple listening positions. The statistical analysis may represent a particular metric of the predicted transfer functions, such as flatness, consistency, efficiency, smoothness, etc. Based on the statistical analysis, the audio system may be configured. For example, values for a single or multiple parameters may be selected based on the statistical analysis, such as the parameters in the predicted transfer functions that maximize or minimize the particular metric. In this manner, the configuration of the audio system may be optimal for the listening positions.

[026] There are many types of statistical analyses that may be performed with the predicted transfer functions. A first type of statistical analysis may indicate consistency of the predicted transfer functions across the multiple listening positions. Examples of the first type include mean spatial variance, mean spatial standard deviation, mean spatial envelope (i.e., min and max), and mean spatial maximum average, if the system is equalized. A second type of statistical analysis may measure flatness of the predicted transfer functions. Examples of the second type include variance of spatial average, standard deviation of the spatial average, envelope of the spatial average, and variance of the spatial minimum. A third type of statistical analysis may measure the differences in overall sound pressure level from seat to seat for the predicted transfer functions. Examples of the third type include variance of mean levels, standard deviation of mean levels, envelope of mean levels, and maximum average of mean levels. The statistical analysis may provide a metric of the differences, such as consistency, flatness or sound pressure level differences, so that the configuration that minimizes or maximizes the metrics (e.g., increases flatness) may be selected.

[027] A fourth type of statistical analysis examines the efficiency of the predicted transfer functions at a single listening position or multiple listening positions. In effect, the statistical analysis may be a measure of the efficiency of the sound system for a particular frequency, frequencies, or range of frequencies at the single listening position or the multiple listening positions. An example of the fourth type includes acoustic efficiency. For a single listening position audio system, the acoustic efficiency may measure the mean level divided by the total drive level for each loudspeaker. For a multiple listening position audio system, the acoustic efficiency may measure the mean overall level divided by the total drive level for each loudspeaker. Acoustic efficiencies for the predicted transfer functions may be examined, and the configuration for the predicted transfer function with a higher or the highest acoustic efficiency may be selected.

[028] A fifth type of statistical analysis examines output of predicted transfer functions at the single listening position or the multiple listening positions. The statistical analysis may be a measure of the raw output of the sound system for a particular frequency, frequencies, or range of frequencies at the single listening position or the multiple listening positions. For an audio system with a single listening position, an example of a statistical analysis examining output includes mean level. For an audio system with multiple listening positions, an example of a statistical analysis examining output includes mean overall level.

A sixth type of statistical analysis examines flatness of predicted transfer functions at a single listening position. The statistical analysis may analyze variations of the predicted transfer functions at the single listening position, such as amplitude variance and amplitude standard deviation.

5 **[029]** The system also provides a methodology for selecting loudspeaker locations, the number of loudspeakers, the types of loudspeakers, correction factors, listening positions, or a combination of these schemes in an audio system that has a single listening position or multiple listening positions. For example, in a given space, loudspeakers may be placed in a multitude of potential positions. The invention includes a system for selecting the
10 loudspeaker locations for the given space. Transfer functions may be measured at the single listening position or the multiple listening positions by placing a loudspeaker at the potential loudspeaker locations and recording the transfer functions at the single listening position or the multiple listening positions. The transfer functions may then be modified based on the
15 example, based on different combinations of potential loudspeaker locations, the transfer functions may be combined to generate the predicted transfer functions. The predicted transfer functions may be statistically analyzed to indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. The selection of the loudspeaker locations may be based on a predicted transfer function that exhibits a desired
20 aspect or set of aspects.

[030] As another example, a given space may allow for different numbers of loudspeakers for the audio system. The invention includes a system for selecting the number of loudspeakers for an audio system in a given space. Transfer functions for the single listening position or the multiple listening positions in the audio system may be modified
25 based on potential numbers of loudspeakers. For example, potential combinations of loudspeakers that are equal to one of the potential number of loudspeakers may be analyzed by combining the transfer functions to generate predicted transfer functions. The predicted transfer functions may be statistically analyzed to indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. The selection of the number
30 of loudspeakers may be based on a predicted transfer function that exhibits a desired aspect or set of aspects.

[031] As still another example, loudspeakers may differ from one another based on a quality or qualities. For example, loudspeakers may differ based on radiation pattern (*e.g.*, monopole versus dipole). The invention includes a system for selecting a type or types of loudspeakers for an audio system having a single listening position or multiple listening positions. Transfer functions may be measured by placing types of loudspeakers at potential loudspeaker locations and recording the transfer functions. For example, each type of loudspeaker may be placed at each potential loudspeaker location and the transfer functions at the listening positions may be recorded. The transfer functions may be modified based on the type of loudspeakers. For example, potential combinations of different types of loudspeakers may be analyzed by combining the transfer functions to generate predicted transfer functions. The predicted transfer functions may be statistically analyzed to indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. The selection of the type or types of loudspeakers may be based on a predicted transfer function that exhibits a desired aspect or set of aspects.

[032] Correction factors may be applied to the audio system. Correction factors may be temporal (*e.g.*, delay) or non-temporal (*e.g.*, gain, amplitude or equalization). The system includes selecting a correction factor or multiple correction factors for an audio system in a given space. Transfer functions for the listening positions may be modified by the potential correction factors to generate predicted transfer functions. The predicted transfer functions may be statistically analyzed to indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. The selection of the correction factors may be based on a predicted transfer function that exhibits a desired aspect or set of aspects.

[033] An audio system may include a plurality of potential listening positions. The system includes selecting a listening position or multiple listening positions from the plurality of potential listening positions. Transfer functions for the potential listening positions may be recorded. The transfer functions may be modified by potential parameters for the audio system, such as potential loudspeaker locations, potential types of speakers, potential correction factors, to generate predicted transfer functions. The predicted transfer functions may be statistically analyzed to indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. The selection of the single listening position or multiple listening positions may be based on a predicted transfer function that exhibits a desired aspect or set of aspects.

[034] Other systems, methods, features, and advantages of the invention will be, or will become, apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the invention, and
5 be protected by the following claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[035] The invention can be better understood with reference to the following drawings and description. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. Moreover, in
10 the figures, like referenced numerals designate corresponding parts throughout the different views.

[036] Figure 1 is a pictorial representation of the first four axial modes for a single room dimension for an instant in time.

[037] Figure 2 is a pictorial representation of the first four axial modes shown in
15 Figure 1 and location for a loudspeaker and listener (smiley face) and two additional listening positions at 1 and 2.

[038] Figure 3 is an example of a multi-subwoofer multi-receiver scenario in a room.

[039] Figure 4 depicts a room having multiple potential subwoofer locations,
20 multiple listening positions, and sound system.

[040] Figure 5 depicts an example sound system 500, measurement device 520, and computational device 570.

[041] Figure 6 is a flow chart of a scheme for improving the low-frequency performance of a sound system.

[042] Figure 7 is an expanded block diagram of block 602 from Figure 6 depicting
25 the selection of sound system parameters.

[043] Figure 8 is an expanded block diagram of block 604 from Figure 6 depicting the input of transfer functions.

[044] Figure 9 is an expanded block diagram of block 606 from Figure 6 depicting
30 modification of the transfer functions.

[045] Figure 10 is a table of illustrative transfer functions and calculations for various statistical analyses that may be performed in block 608 from Figure 6.

[046] Figure 11 is an expanded block diagram of block 608 from Figure 6 depicting statistical analyses for acoustic efficiency and mean spatial variance.

5 [047] Figure 12 is an expanded block diagram of block 608 from Figure 6 depicting statistical analyses for acoustic efficiency and variance of the spatial average

[048] Figure 13 is a table of illustrative solution sets for selected parameters generated in response to a statistical analysis.

10 [049] Figure 14 is an expanded block diagram of block 612 from Figure 6 depicting the implementation of values for the selected solution in the sound system.

[050] Figure 15 is an example of a layout of a listening room in Example 1.

[051] Figure 16 is a graph of low frequency performance for the listening room in Example 1 without low frequency optimization.

15 [052] Figure 17 is a graph of predicted low frequency performance for the listening room in Example 1 with low frequency optimization.

[053] Figure 18 is an example of a layout of a dedicated home theater system in Example 2.

[054] Figure 19 is a graph of low frequency performance for the dedicated home theater system in Example 2 without low frequency optimization.

20 [055] Figure 20 is a graph of predicted low frequency performance for the dedicated home theater system in Example 2 with low frequency optimization.

[056] Figure 21 is an example of a layout of a family room home theater system in Example 3.

25 [057] Figure 22 is a graph of low frequency performance for the family room home theater system in Example 3 without low frequency optimization and with only the front two subwoofers active (subwoofers 1 and 2 shown in Figure 21).

[058] Figure 23 is a graph of predicted low frequency performance for the family room home theater system in Example 3 with low frequency optimization applied to the front two subwoofers (subwoofers 1 and 2 shown in Figure 21).

30 [059] Figure 24 is a graph of predicted low frequency performance for the family room home theater system in Example 3 with low frequency optimization applied to the four subwoofers in the system (subwoofers 1, 2, 3, and 4 shown in Figure 21).

[060] Figure 25 is an example of a layout of an open room home theater system in Example 4.

[061] Figure 26 is a graph of low frequency performance for the open room home theater system in Example 4 without low frequency optimization and with only subwoofer 1 shown in Figure 25 active.

[062] Figure 27 is a graph of predicted low frequency performance for the open room home theater system in Example 4 with low frequency optimization used to determine that subwoofer locations 1, 2, 4, and 5 shown in Figure 25 are optimum.

[063] Figure 28 is an example of a layout of an engineering listening room in Example 5.

[064] Figure 29 is a graph of predicted low frequency performance for the engineering listening room in Example 5 without low frequency optimization and with only subwoofer 1 shown in Figure 28 active.

[065] Figure 30 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization for one active subwoofer.

[066] Figure 31 is a graph of predicted low frequency performance for the engineering listening room in Example 5 without low frequency optimization with the two front corner subwoofers active (subwoofers 1 and 3 shown in Figure 28).

[067] Figure 32 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization for two active subwoofers.

[068] Figure 33 is a graph of predicted low frequency performance for the engineering listening room in Example 5 without low frequency optimization using a four-corner subwoofer configuration (subwoofers 1, 3, 5, and 7 shown in Figure 28).

[069] Figure 34 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization using a four-corner subwoofer configuration (subwoofers 1, 3, 5, and 7 shown in Figure 28).

[070] Figure 35 is a graph of predicted low frequency performance for the engineering listening room in Example 5 without low frequency optimization using a four-midpoint subwoofer configuration (subwoofers 2, 4, 6, and 8 shown in Figure 28).

[071] Figure 36 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization using a four-midpoint subwoofer configuration (subwoofers 2, 4, 6, and 8 shown in Figure 28).

5 [072] Figure 37 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization determining an optimum four-subwoofer configuration based on using spatial variance as the ranking factor (subwoofers 2, 5, 6, and 7 shown in Figure 28).

10 [073] Figure 38 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization determining an optimum four-subwoofer configuration based on using spatial variance and variance of the spatial average as the ranking factors (subwoofers 1, 5, 6, and 7 shown in Figure 28).

15 [074] Figure 39 is a graph of predicted low frequency performance for the engineering listening room in Example 5 with low frequency optimization determining an optimum four-subwoofer configuration based on using spatial variance and acoustic efficiency as the ranking factors (subwoofers 1, 5, 6, and 7 shown in Figure 28).

[075] Figure 40 is a graph ranking the solutions by spatial variance for the low frequency performance in Figures 29-39.

20 [076] Figure 41 is a graph of predicted low frequency performance for the engineering listening room in Example 5 using four-corner subwoofer configuration (subwoofers 1, 3, 5, and 7 shown in Figure 28) with gain and delay being optimized.

[077] Figure 42 is a graph of measured low frequency performance for the engineering listening room in Example 5 using four-corner subwoofer configuration (subwoofers 1, 3, 5, and 7 shown in Figure 28) with gain and delay being optimized.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[078] Figure 4 depicts a room 400 defined by room boundary walls 402 where audio performance, such as low-frequency performance, may be improved by the described method. Room 400 may comprise any type of space in which the loudspeaker is placed. The space may have fully enclosed boundaries, such as a room with the door closed or a vehicle interior; or partially enclosed boundaries, such as a room with a connected hallway, open door, or open wall; or a vehicle with an open sunroof. Low-frequency performance in a space will be described with respect to a room in the specification and appended claims; however, it is to be understood that vehicle interiors, recording studios, domestic living spaces, concert halls, movie theaters, partially enclosed spaces, and the like are also included. Room boundaries, such as room boundary walls 402, include the partitions that partially or fully enclose a room. Room boundaries may be made from any material, such as gypsum, wood, concrete, glass, leather, textile, and plastic. In a home, room boundaries are often made from gypsum, masonry, or textiles. Boundaries may include walls, draperies, furniture, furnishings, and the like. In vehicles, room boundaries are often made from plastic, leather, vinyl, glass, and the like. Room boundaries have varying abilities to reflect, diffuse, and absorb sound. The acoustic character of a room boundary may affect the acoustic signal.

[079] Room 400 includes a sound system 470 that may include a source 412, such as a CD player, tuner, DVD player, and the like, an optional processor 404, an amplifier 410, and a loudspeaker 414. Dashed line 470 represents that the source 412, optional processor 404, amplifier 410, and loudspeaker 414 may be included in the sound system.

[080] Loudspeaker 414 may include a loudspeaker enclosure that typically has a box-like configuration enclosing the transducer. The loudspeaker enclosure may have other shapes and configurations including those that conform to environmental conditions of the loudspeaker location, such as in a wall or vehicle. The loudspeaker may also utilize a portion of the wall or vehicle as all or a portion of its enclosure.

[081] The loudspeaker may provide a full range of acoustical frequencies from low to high. Many loudspeakers have multiple transducers in the enclosure. When multiple transducers are utilized in the loudspeaker enclosure, it is common for individual transducers to operate more effectively in different frequency bands. The loudspeaker or a portion of the

loudspeaker may be optimized to provide a particular range of acoustical frequencies, such as low-frequencies. The loudspeaker may include a dedicated amplifier, gain control, equalizer, and the like. The loudspeaker may have other configurations including those with fewer or additional components.

5 **[082]** A loudspeaker or a portion of a loudspeaker including a transducer that is optimized to produce low-frequencies is commonly referred to as a subwoofer. A subwoofer may include any transducer capable of producing low-frequencies. Unless stated otherwise, loudspeakers capable of producing low-frequencies will be referred to by the term subwoofer in the specification and appended claims; however, any loudspeaker or portion of a
10 loudspeaker capable of producing low-frequencies and responding to a common electrical signal is included.

[083] The room includes eight potential loudspeaker locations 440-447, where one or more loudspeakers may be placed. Fewer or greater numbers of potential loudspeaker locations may be included. Loudspeaker location or "location" is a physical place in a space
15 where a loudspeaker, such as a subwoofer, may be situated. Locations may include the corners, walls, or ceiling of a room in a house, or the interior panels of a vehicle.

[084] The room also includes six listening positions 450-455, where listeners may sit. Fewer or greater numbers of listening positions may likewise be included. Listening position or "position" is a physical area in a space where a listener may be seated or standing.
20 Positions may include couches or chairs in a home or the driver's or pilot's seat in a vehicle. While a listening position may be anywhere in the room, they are generally selected based on aesthetic and ergonomic concerns. Listening positions may also be selected on the basis of good high- and mid-frequency acoustic performance.

[085] By positioning the loudspeaker 414 at each of the potential loudspeaker
25 locations 440-447 and measuring at each of the listening positions 450-455, a transfer function may be determined at each of the listening positions 450-455 for each of the potential loudspeaker locations 440-447. The transfer function may measure frequencies in various ranges, such as below about 120 Hertz (Hz), below about 100 Hz, below about 80 Hz, below about 60 Hz, below about 50 Hz, below about 40 Hz, or between 20 Hz and 80 Hz.
30 For example, a transfer function, such as a frequency response, may be determined at the first listening position 450 for the first potential loudspeaker location 440. The determination may then be repeated at the first listening position 450 for each of the remaining potential

loudspeaker locations 441-447. When multiple listening positions are considered, the transfer function determination may be repeated at the second listening position 451 for each of the potential loudspeaker locations 440-447, and so on until reaching the last listening position 455. In the configuration shown in Figure 4, eight transfer functions may be
5 determined for each of the listening positions 450-455, resulting in a total of 48 transfer functions being determined for room 400.

[086] If more than one type of loudspeaker is used, such as type A loudspeaker and type B loudspeaker, two transfer functions may be determined for each potential location. Type A loudspeaker and type B loudspeaker may have different qualities. As merely one
10 example, type A loudspeaker may be a dipole loudspeaker and type B loudspeaker may be a convention (monopole) loudspeaker. In the example of eight potential loudspeaker locations, for each potential location, such as location 440, a 140A transfer function and a 140B transfer function may be determined for each listening position 450-455. While further use of the term location is limited to the use of one type of loudspeaker for simplicity, multiple types of
15 loudspeakers may be considered.

[087] The determined transfer function may measure any acoustical aspect. For example, the determined transfer function may comprise an amplitude or loudness component and a phase component. Any method that yields amplitude and phase values, if desired, may be appropriate to determine a transfer function. The amplitude and phase components of the
20 transfer function may be expressed as vectors. The transfer function may be determined at one or at a plurality of frequencies or tones, such as periodically at every 2 Hz from 20 Hz to 20,000 Hz. The spacing of frequencies considered may be referred to as the frequency resolution.

[088] The transfer function may reflect the amplitude and/or phase deviations that
25 occur in an acoustic signal as it travels from the loudspeaker 414, interacts with the room boundaries 402, and reaches the listening positions 450-455. The transfer function may reflect the deviations introduced by irregular, non-parallelogram shaped rooms and rooms that are not fully enclosed. It is not necessary to measure room dimensions, the acoustic effect of room boundary 402, and the like to determine a transfer function. Instead, an
30 acoustic signal may be output from the loudspeaker 414 that is located at one of the potential locations 440-447 and recorded by a microphone or other acoustic measuring device located at one of the listening positions 450-455.

[089] With reference to Figure 5, a system for implementing the invention may comprise a sound system 500, a measurement device 520, and a computational device 570. The sound system may comprise a general purpose sound system with a sound processor 502, external components 512, and loudspeakers 1 to N 514, 516, and 518. The sound system may have other configurations including those with fewer or additional components.

[090] The sound processor 502 may comprise a receiver, a preamplifier, a surround sound processor, and the like. The sound processor 502 may operate in the digital domain, the analog domain, or a combination of both. The sound processor 502 may include a processor 504 and a memory 506. The processor 504 may perform arithmetic, logic and/or control operations by accessing system memory 506. The sound processor 502 may further include an input/output (I/O) 508. The I/O 508 may receive input and send output to measurement device 520 and to external components 512, as discussed below.

[091] The sound processor 502 may further include amplifier 510 that is in communication with processor 504. Amplifier 510 may operate in the digital domain, the analog domain, or a combination of both. Amplifier 510 may send control information (such as current) to one or more loudspeakers in order to control the audio output of the loudspeakers. Examples of loudspeakers include loudspeakers 1 to N 514, 516, and 518. Alternatively, loudspeakers 1 to N 514, 516, and 518 may include amplifiers and/or other control circuitry. Loudspeakers 1 to N 514, 516, and 518 may be identical loudspeakers in terms of efficiency (acoustic output for a given power input) and design. Alternatively, loudspeakers 1 to N 514, 516, and 518 may be different from one another in terms of efficiency and design. Sound processor 502 may receive input from and send output to external components 512. Examples of external components 512 include, without limitation, a turntable, a CD player, a tuner, and a DVD player. Depending on the configuration, one or more digital to analog converters (DAC) (not shown) may be implemented after external components 512, processor 504, or amplifier 510.

[092] Measurement device 520 enables measurement of acoustic signals output from sound system 500 including, for example: (1) the amplitude of the acoustic signal output at one, some, or a range of frequencies; and/or (2) the amplitude and phase of the acoustic signal output at one, some, or a range of frequencies. One example of a measurement device is a sound pressure level meter, which may determine the amplitude of the acoustic signals. Another example of a measurement device is a transfer function analyzer, which may

determine the amplitude and phase of the acoustic signals. The transfer function analyzer may plot the data and produce output files that may be sent to a computational device 570 for processing, as discussed below.

[093] Measurement device 520 may comprise a general purpose computing device that includes the ability to measure acoustic signals. For example, a transfer function analyzer PCI Card 562 may be included in measurement device 520 to provide the audio measuring functionality. Alternatively, the measurement device 520 may comprise a device with functionality dedicated to a transfer function analyzer.

[094] Measurement device 520 may include a processing unit 532, a system memory 522, and a system bus 538 that couples various system components including the system memory 522 to the processing unit 532. The processing unit 532 may perform arithmetic, logic and/or control operations by accessing system memory 522. The system memory 522 may store information and/or instructions for use in combination with the processing unit 532. The system memory 522 may include volatile and non-volatile memory, such as random access memory (RAM) 524 and read only memory (ROM) 530. A basic input/output system (BIOS) may be stored in ROM 530. The BIOS may contain the basic routines that helps to transfer information between elements within the measurement device 520, such as during start-up, may be stored in ROM 530. The system bus 538 may be any of several types of bus structures including a memory bus or memory controller, a peripheral bus, and a local bus using any of a variety of bus architectures.

[095] The measurement device 520 may further include a hard disk drive 542 for reading from and writing to a hard disk (not shown), and an external disk drive 546 for reading from or writing to a removable external disk 548. The removable disk may be a magnetic disk for a magnetic disk driver or an optical disk such as a CD ROM for an optical disk drive. Output files generated by the transfer function device, discussed above, may be stored on removable external disk 548, and may be transferred to computational device 570 for further processing. The measurement device may have other configurations including those with fewer or additional components.

[096] The hard disk drive 542 and external disk drive 546 may be connected to the system bus 538 by a hard disk drive interface 540 and an external disk drive interface 544, respectively. The drives and their associated computer-readable media may provide nonvolatile storage of computer readable instructions, data structures, program modules, and

other data for the measurement device 520. Although the exemplary environment described in Figure 4 employs a hard disk and an external disk 548, other types of computer readable media may be used which can store data that is accessible by a computer, such as magnetic cassettes, flash memory cards, random access memories, read only memories, and the like, may also be used in the exemplary operating environment.

[097] A number of program modules may be stored on the hard disk, external disk 548, ROM 530 or RAM 524, including an operating system (not shown), one or more application programs 526, other program modules (not shown), and program data 528. One such application program may include the functionality of the transfer function analyzer that may be downloaded from the transfer function PCI card 562.

[098] A user may enter commands and/or information into measurement device 520 through input devices such as keyboard 558. Audio output may be measured using microphone 560. Other input devices (not shown) may include a mouse or other pointing device, sensors other than microphone 560, joystick, game pad, scanner, or the like. These and other input devices may be connected to the processing unit 532 through a serial port interface 554 that is coupled to the system bus 538, or may be collected by other interfaces, such as a parallel port interface 550, game port or a universal serial bus (USB). Further, information may be printed using printer 552. The printer 552 and other parallel input/output devices may be connected to the processing unit 532 through parallel port interface 550. A monitor 537, or other type of display device, is also connected to the system bus 538 via an interface, such as a video input/output 536. In addition to the monitor 537, measurement device 520 may include other peripheral output devices (not shown), such as loudspeakers or other audible output.

[099] As discussed in more detail below, measurement device 520 may communicate with other electronic devices such as sound system 500 in order to measure acoustic signals in various parts of a room. One of the loudspeakers 514, 516, and 518 may be positioned at one, some, or all of the potential loudspeaker locations 440-447. The microphone 560, or other type of acoustic signal sensor, may be positioned at one, some, or all of the potential listening positions 450-455. The sound system 500 may control the loudspeaker to emit a predetermined acoustic signal. The acoustic signal output from the loudspeaker may then be sensed at the listening position by the microphone 560. The

measurement device 520 may then record the various aspects of the output acoustic signal, such as amplitude and phase.

[0100] Control of the sound system 500 to emit the predetermined acoustic signals may be performed in several ways. The measurement device 520 may provide commands from the input/output (I/O) 534 via the line 564 to the I/O 508 in order to control the sound system 500. The sound system may then emit a predetermined acoustic signal based on the command from the measurement device. The sound system also may send a predetermined signal to the positioned loudspeaker without receiving commands from measurement device. For example, external component 212 may comprise a CD player. A specific CD may be inserted into the CD player and played. During play, the acoustic signal output from the loudspeaker may be sensed at the listening position by microphone 560.

[0101] The measured acoustic signal output from the different loudspeaker locations for the different listening positions may be stored, such as on the external disk 548. The external disk 548 may be input to the computational device 570. The computational device 570 may be another computing environment and may include many or all of the elements described above relative to the measurement device 520. The computational device 570 may include a processing unit with capability greater than the processing unit 532 in order to perform the numerically intensive statistical analyses discussed below.

[0102] As discussed further below, corrections may be implemented in the sound processor 502, the processor 504, the amplifier 510, the loudspeaker 1 to N 514, 516, and 518, or at multiple locations in sound system 500. The sound processor 502 may implement a time delay prior to digital to analog conversion. Sound processor 502 may implement gain correction and/or equalization in the analog or digital domain. Correction settings, such as a 6 dB amplitude reduction for the loudspeaker 514, may be input to the sound processor 502 by the user. The implementation of the settings also may be automated by the sound system 500.

[0103] As shown in Figure 5, the measurement device 520 is separate from the sound system 500. Alternatively, the functionality of the measurement device 520 may be incorporated within the sound system 500. Further, as shown in Figure 5, the measurement device 520 is separate from the computational device 570. If the measurement device 520 has sufficient computation capability, computational device 570 need not be used so that measurement device 520 may both measure and provide the below described computations.

The sound system 500, the measurement device 520, and the computational device 570 may have other configurations including those with fewer or additional components.

[0104] Figure 6 is a flow chart 600 depicting an overview of a methodology for selecting a configuration to improve the performance, such as low-frequency performance, of a sound system. The configuration of the sound system may comprise a parameter or set of parameters for the sound system. Parameters may include any aspect that affects transfer functions at the listening position or positions including, for example: (1) the location for loudspeakers; (2) the number of loudspeakers; (3) the type of loudspeakers; (4) correction settings; and (5) the listening positions.

[0105] To analyze the potential configurations of the audio system, potential values for the parameters may be selected, as shown at block 602. For example, potential locations for loudspeakers may be selected. The potential locations may comprise any location in the given space where a loudspeaker may be positioned. For example, the potential locations may comprise a discrete set of potential locations input by a user, such as the eight potential loudspeaker locations 440-447 shown in Figure 4. As another example, the potential number of loudspeakers may be selected. The potential number of loudspeakers may comprise any possible number of loudspeakers in a given space. The number may comprise an upper limit, a lower limit, or an upper and lower limit. For example, the potential number of loudspeakers may comprise a minimum and a maximum number of loudspeakers. As still another example, the potential type of loudspeakers may be selected. The type of loudspeakers may comprise different qualities of the loudspeakers. For example, the types of loudspeaker may include dipole loudspeakers and monopole loudspeakers. In still another example, a space may include a discrete number of potential listening positions. Typically, the listening positions are predetermined and not subject to change. However, flexible space configurations may allow for selection of one or more listening positions from a plurality of potential listening positions.

[0106] Potential values for correction settings may also be selected. The correction settings may comprise adjustments that provide improved low-frequency performance independent of loudspeaker placement when implemented in the sound system 500. The corrections may be applied to one or more of the loudspeakers. While corrections may be combined with optimized loudspeaker number and location, either may be independently considered to improve frequency performance, including low-frequency performance.

Examples of correction settings include corrections to gain, delay, and equalization. The selection of sound system parameters is discussed in greater detail with regard to Figure 7.

[0107] Transfer functions for the potential loudspeaker locations at the single or multiple listening positions may be input, as shown at block 604. The measurements for the determined transfer functions may be performed using MLSSA Acoustical Measurement System with 2 Hz resolution. A more detailed description of a flow chart for transfer function determination is discussed below with regard to Figure 8.

[0108] The transfer functions may be modified based on the potential values for the sound system parameters, as shown at block 606. The potential values for the sound system parameters may be combined to represent potential configurations of the audio system. For example, the potential values may represent potential combinations of speakers, potential correction factors, potential types of loudspeakers, potential listening positions, or any combination of potential parameters, such as potential combination of speakers and potential correction factors. The transfer functions previously recorded may be combined and/or adjusted based on the potential configurations of the system. The modified transfer functions may therefore represent predicted transfer functions for a sound system in the potential configurations. The modification of the transfer functions is discussed in greater detail with regard to Figure 9.

[0109] One or more analysis techniques, such as statistical analysis techniques, may then be applied to the predicted transfer functions, as shown at block 608. The statistical analysis may be used to evaluate different configurations of the audio system, including one or more values for the potential values for the parameters. Specifically, the statistical analysis may provide a rational approach to improving the frequency performance for the sound system, including improving low-frequency performance, by considering the combined effect of multiple sound system parameters, individually or in concert. The statistical analysis may measure various aspects or metrics regarding the predicted transfer functions. For example, the statistical analysis may indicate certain aspects of the predicted transfer functions, such as flatness, consistency, efficiency, etc. Specifically, when examining an audio system with a single listening position, the statistical analysis may analyze efficiency or flatness of the predicted transfer functions for the single listening position. When examining an audio system with multiple listening positions, the statistical analysis may analyze the

predicted transfer functions for efficiency, flatness, or variation across the listening positions. Examples of the statistical analyses are discussed with respect to Figures 10-12.

[0110] Based on the statistical analysis, values for the parameters may be selected, as shown at block 610. The statistical analysis, which may measure various aspects of the predicted transfer functions, may be used to compare the predicted transfer functions with one another. One method of comparison is by ranking the potential configurations with regard to a determined value, such as an amplitude or variance. For example, after mean spatial variance, variance of the spatial average, and acoustic efficiency for each potential solution are calculated, results may be ranked and the best configuration selected. Assuming that there is no configuration that is highest ranked in all categories (*e.g.*, lowest mean spatial variance, lowest variance of the spatial average, and highest acoustic efficiency factor), these metrics may be prioritized or weighted. The parameters for the potential configuration that is better, or the best, when compared with other potential configurations, may then be selected.

[0111] Values corresponding to the selected solution may then be implemented in the sound system, as shown at block 612 and described in more detail in Figure 14. After implementation of the solution values, global correction methods of improving low-frequency performance may be applied equally or substantially equally to all loudspeakers in the system 500 to improve low-frequency performance further, as shown at block 614. The transfer function of the sound system may then be re-measured to confirm the improvement in performance. Flow chart 600 may include fewer or additional steps not depicted in Figure 6.

[0112] Global equalization is one type of global correction method for improving low-frequency performance. Global equalization may be applied equally or substantially equally to all loudspeakers in the sound system 500. Since the statistical analysis may determine solutions that favor peaks in relation to dips in the amplitude response, global equalization may be applied to reduce the amplitude of the resultant peak or peaks. Thus, a further improvement of low-frequency performance may be achieved after a solution is selected and implemented in blocks 610 and 612. Additional parametric or any other type of equalization may be utilized to implement global equalization, as shown at block 614. The statistical analysis may determine optimized global equalization parameters by modifying the previously modified amplitude values for all loudspeakers in a substantially equal manner.

[0113] SELECTING POTENTIAL PARAMETERS

[0114] Figure 7 is an expanded block diagram of block 602 from Figure 6, depicting the selection of potential audio system parameters. The method may include selecting one listening position or a plurality of listening positions over which to improve frequency performance, as shown at block 702. For example, in instances where the listening positions may be selected from a plurality of potential listening positions (*e.g.*, selecting two listening positions from five potential listening positions), the potential listening positions may be input. The method may further include selecting the potential locations where loudspeakers can be placed, as shown at block 704. This selection may be based on aesthetic or other considerations. In addition, if more than one type of loudspeaker is contemplated in the analysis, the types of loudspeakers may be selected. The frequency resolution may also be selected, as shown at block 706. The selection of the frequency resolution may be based on the level of resolution desired and the computational capability of computational device 570. The user may further select the minimum and maximum number of loudspeakers that will be placed at the potential locations, as shown at blocks 708 and 710. For example, a minimum of 1 loudspeaker and a maximum of 3 loudspeakers may be considered for 4 potential loudspeaker locations.

[0115] Blocks 712, 714 and 716 depict the selection of correction settings or “corrections” that may be considered for later implementation at a specific loudspeaker location or locations. As discussed above, corrections comprise adjustments that may provide improved low-frequency performance independent of loudspeaker placement when implemented in the sound system. Corrections may be independently determined during statistical analysis for each potential loudspeaker location and independently implemented for each loudspeaker placed.

[0116] The number and value of gain settings to be considered at each potential loudspeaker location may be selected, as shown at block 712. Unlike the equalization levels discussed below, gain settings may affect all frequencies reproduced by the loudspeaker, thus being frequency-independent, and are commonly referred to as loudness or volume settings. While any number and value of gain settings may be selected to consider at each potential loudspeaker location, three gain settings of 0, -6, and -12 dB may be selected. These values are expressed in terms of dB reductions from a baseline acoustic output of 0 dB or unity; however, dB values are relative, so increases may also be utilized.

[0117] The number and value of delay settings to be considered at each potential loudspeaker location may be selected, as shown at block 714. By introducing a delay into a loudspeaker, the phase of the reproduced acoustic signal may be altered. Any number and value of delay settings may be selected for consideration at each potential loudspeaker location. For example, three delay settings of 0, 5, and 10 milliseconds may be selected.

[0118] The number and value of equalization settings to be applied at each potential loudspeaker location may be selected, as shown at block 716. Equalization may comprise various types of analog or digital equalization including parametric, graphic, paragraphic, shelving, FIR (finite impulse response), and transversal equalization. Equalization settings may include a frequency setting (*e.g.*, a center frequency), a bandwidth setting (*e.g.*, the bandwidth around the center frequency to apply the equalization filter), a level setting (*e.g.*, the amount that the amplitude reduces or increases the signal), and the like. Thus, for one potential loudspeaker location, more than one equalization setting may be applied, such as a first equalization setting at a first center frequency and a second equalization setting at a second center frequency or such as different types of equalizations. Further, equalization may be applied to all frequencies of interest. For example, in low-frequency analysis focusing on 20-80 Hz, equalization may be applied to all frequencies of interest. To reduce processing time, the frequency having the greatest variance may be selected as further described in relation to block 1106 of Figure 11. If frequency selection is limited in this manner, three bandwidth and three level parameters may be selected. Bandwidth may be conveniently expressed in terms of Filter Q (Q). Q may be defined as the center frequency in Hertz divided by the frequency range in Hz over which the level adjustment is applied. For example, if a center frequency of 50 Hz is chosen, the bandwidth is 25 Hz for a Q of 2. Suitable Q parameters include, but are not limited to, 1, 4, and 16. Suitable level parameters include, but are not limited to, 0, -6, and -12 dB.

[0119] Based on the selections made in 702 through 716, the number of transfer functions to be considered during statistical analysis may be determined, as shown at block 718. These transfer functions may include those modified with one or more correction settings, those for a single loudspeaker location, and those combined to represent a plurality of loudspeaker locations. It may be impractical to search all possible combinations of loudspeaker location, loudspeaker number, gain settings, delay settings, equalization settings, and the like. If impractical, a subset of the potential solutions may be examined. The subset

may be chosen with sufficient resolution, which is not too coarse that it may miss the best solutions or too fine that it may take too long to search. Changing search parameter step size greatly affects computation time. Changing the search parameters may be estimated using (4):

$$5 \quad [0120] \quad T \approx \left(\frac{N}{K} \right) A^K T^K F_L F_Q Perm(k) S T_{ref} \quad (4)$$

where: T is the estimated calculation time

T_{ref} is the time required to search one unique combination of loudspeaker location, loudspeaker number, gain settings, delay settings, equalization settings, and the like

N is the number of potential loudspeaker locations;

10 K is the actual number of loudspeakers to be used;

A is the number of loudspeaker amplitude levels searched;

T is the number of signal delay values searched;

F_L is the number of filter cut levels searched;

F_Q is the number of filter Q values searched;

15 S is the number of listening positions being optimized;

$\binom{X}{Y}$ is the number of possible ways of choosing from N possible loudspeaker

locations K at a time, with $\binom{X}{Y} = \frac{X!}{Y!(X-Y)!}$

perm(K) is the number of permutations of K loudspeakers, with $perm(K) = K!$

[0121] While any number of transfer functions may be considered during statistical
20 analysis in block 606, if a shorter calculation time is desired, the selected frequency resolution, selected number of loudspeakers, selected number of corrections, and/or correction settings, for example, may be reduced, as shown at block 722. When an acceptable number of transfer functions for statistical analysis is determined, as shown at block 720, the transfer functions may be input. Block 602 may contain fewer or additional
25 steps not depicted in Figure 7.

[0122] RECORDING TRANSFER FUNCTIONS

[0123] Figure 8 is an expanded block diagram of block 604 from Figure 6 depicting the input of transfer functions corresponding to a specific loudspeaker location for each listening position. A loudspeaker may be placed at the first potential location, such as

location 440 of Figure 4, as shown at block 802. A microphone (or other acoustic sensor) may then be placed at the first listening position, such as position 450 of Figure 4, as shown at block 804. A transfer function for the first potential loudspeaker location at the first listening position may then be recorded in response to an acoustic signal generated by the sound system 500 with measurement device 520, as shown at block 806. This procedure is described in greater detail with regard to Figures 4 and 5.

[0124] If additional listening positions remain (including additional potential listening positions), as shown at block 808, the microphone may be moved to the next listening position, as shown at block 810. For example, the microphone may be moved to position 451 of Figure 4. The measurement may then be repeated, as shown at block 806. If additional potential loudspeaker locations remain, as shown at block 812, the loudspeaker may be moved to the next potential location, as shown at block 814. For example, the loudspeaker may be moved to location 441 of Figure 4. The measurement may then be repeated, as shown at block 806. This procedure may be repeated until transfer functions are recorded for all potential loudspeaker locations at each listening position. Block 604 may contain fewer or additional steps not depicted in Figure 8.

[0125] MODIFYING THE TRANSFER FUNCTIONS

[0126] The recorded transfer functions may be modified based on potential configurations of the audio system in order to determine predicted transfer functions. The potential configurations may include any single potential parameter value, or any combination or sub-combination of potential parameter values in the audio system, and various permutations thereof. For example, the potential configurations may comprise different loudspeaker locations, different types of loudspeakers, different correction factors, or any combination or sub-combination of loudspeaker locations, types of loudspeakers, or correction factors. The modification of the transfer functions may include combining transfer functions and/or adjusting transfer functions. The modified transfer function may represent the predicted transfer function at the single listening position for the potential parameter values (*i.e.*, the potential positions of the loudspeakers, the potential types of loudspeakers, the potential correction settings, etc.).

[0127] In one example of combining transfer functions, a potential configuration may include placing loudspeakers in positions 440 and 442, and a listening position of interest 451. Two transfer functions (one for registering a transfer function at position 451 when

loudspeaker is at position 440 and a second for registering a transfer function at position 451 when loudspeaker is at position 442) may be accessed from memory and combined in order to predict the two-loudspeaker configuration. As discussed below, superposition may be used to combine the transfer functions. The combined transfer functions thus describe the acoustic signal at a listening position generated by multiple loudspeakers at positions 440 and 442. As another example of combining transfer functions, the transfer functions for specific types of loudspeaker may be accessed. If one potential loudspeaker solution includes placing loudspeaker of type A in position 440 and loudspeaker of type B in position 442, and the listening position of interest is 451, two transfer functions (one for registering a transfer function at position 451 when a loudspeaker of type A is at position 440 and a second for registering a transfer function at position 451 when a loudspeaker of type B is at position 442) may be accessed from memory and combined to predict the configuration.

[0128] Moreover, an example of adjusting the transfer functions may include changing the transfer functions based on correction settings. After selecting the desired transfer functions, the one or more selected transfer functions may be modified with one or more potential correction settings, such as a gain setting, delay setting, or equalization setting. The modified transfer functions may represent predicted transfer functions for the potential correction settings.

[0129] Figure 9 is an expanded block diagram of block 606 from Figure 6 depicting the modification of the transfer functions. The user or the program executing in computational device 570 may select a specific listening position, as shown at block 902. For example, if the room environment includes two listening positions (*e.g.*, 451 and 452 in Figure 4), either listening position may be selected. The user or the program executing in computational device 570 may then select a single or a combination of potential loudspeaker locations, as shown at block 904. For example, if the room environment includes two potential loudspeaker locations (*e.g.*, 440 and 442 in Figure 4), any single or combination of loudspeaker locations (*e.g.*, 440, 442, or 440 and 442) may be selected. The user or the program executing in computational device 570 may then select transfer functions for the selected listening position that corresponds to the selected loudspeaker location or the combination of loudspeaker locations, as shown at block 906. For example, if the listening position is 451 and the potential loudspeaker locations are 440 and 442, the transfer functions

at position 451 when loudspeaker is at position 440 and at position 451 when loudspeaker is at position 442 may be selected.

[0130] If the transfer functions include a phase component, the program executing in computational device 570 may modify the phase component of the measured transfer function stored in memory with any delay settings selected in block 714, as shown at block 908. For example, if one of the optional delay settings comprises a 10 millisecond differential delay between two loudspeakers, the phase component of one of the transfer functions may be modified to reflect the introduction of a 10 millisecond time delay factor. In the example discussed above, if the potential loudspeaker locations are 440 and 442, the transfer function at position 451 for the loudspeaker at location 440 may be delayed 10 milliseconds relative to the transfer function at position 451 for the loudspeaker at location 442. For example, the transfer function at position 451 for the loudspeaker at location 440 may be delayed by 10 milliseconds. Or, the transfer function at position 451 for the loudspeaker at location 442 may be advanced by 10 milliseconds. Or, a combination of changing both transfer functions may result is a relative delay between the transfer functions of 10 milliseconds. In this manner, one or a plurality of delay settings may be applied to modify the recorded transfer function at each loudspeaker location.

[0131] The program executing in computational device 570 may modify the amplitude component of the measured transfer function stored in memory with any gain settings selected in block 712, as shown at block 910. Thus, numerical amplitude components can be increased or reduced by a set amount, such as 6 dB. Specifically, one, some, or all of the amplitudes of the transfer functions may be modified. In the example discussed above, the amplitude of the transfer function at position 451 for the loudspeaker at location 442 may be increased or decreased relative to the amplitude of the transfer function at position 451 for the loudspeaker at location 440. For example, the transfer function at position 451 for the loudspeaker at location 442 may be decreased by 6 dB. Or, the transfer function at position 451 for the loudspeaker at location 440 may be increased by 6 dB. Or, a combination of changing both transfer functions may result is a relative amplitude difference between the transfer functions of 6 dB. In this manner, one of a plurality of gain settings may be applied to each subwoofer to modify the recorded transfer function at each listening position.

[0132] While not depicted in Figure 9, prior to the combination in block 912, the program executing in computational device 570 shown in Figure 5 may modify the amplitude component of the stored transfer function with any equalization settings, such as the equalization settings selected in block 716. As discussed above, equalization settings, including a center frequency, a bandwidth and an amplitude adjustment, may modify the transfer function. The choice of the center frequency, the bandwidth, and amplitude adjustment, may be limited due to computational complexity. Specifically, calculating and applying the equalization filters at all possible frequencies with multiple boost/cut levels and Q values may increase calculation time enormously if equalization modifications are performed prior to the combination in block 912. If shorter calculation times are desired, equalization setting modifications may be performed in block 1108 after determining the frequency of the maximum spatial variance, as discussed more fully in regard to Figure 11 below. For example, an equalization filter may be applied with a center frequency equal to the frequency of a solution with the maximum variance, thereby reducing spatial variance. This greatly reduces the computation time, since only one frequency is calculated for each filter/loudspeaker. Or, the equalization settings may be implemented prior to maximum variance determination.

[0133] The program executing in computational device 570 may combine the recorded or modified transfer functions (*e.g.*, modified by correction factors such as delay, gain, and/or equalization) to give a combined amplitude response for the selected combination of loudspeaker locations at the listening position, as shown in block 912. For example, the transfer function at position 451 for the loudspeaker at location 440 may be unmodified (no correction factors applied) and the transfer function at position 451 for the loudspeaker at location 440 may be modified to introduce a delay and an amplitude change. At least a portion of the transfer functions may be combined to give a combined response. For example, the amplitude component of the transfer functions may be combined. For example, the amplitude and the phase components of the transfer functions may be combined.

[0134] One method of combining the transfer functions may include superposition. The principle of superposition may apply if it is assumed that the loudspeaker, room, and signal processing comprise a linear system. Superposition includes the linear addition of transfer function vectors. The vectors may be added or summed for each individual frequency of the transfer function. For example, if transfer function vectors are measured at

listening position 451 for loudspeaker locations 440, 441, and 442, the vectors at each frequency may be summed to give a three-loudspeaker location combined amplitude response at each frequency. Transfer function or transfer function values modified with at least one correction setting, such as gain, equalization, or delay settings, may also be combined.

5 **[0135]** If there are unexamined combinations of loudspeaker locations for the listening position selected in block 902, blocks 904 through 912 may be repeated, as shown in block 914. If additional delay settings were selected in block 714, blocks 908 through 914 may be repeated, as shown in block 916. If additional gain settings were selected in block 712, blocks 910 through 916 may be repeated, as shown in block 918. If additional listening
10 positions were selected in block 702, blocks 902 through 918 may be repeated, as shown in block 920. When all listening positions, potential loudspeaker locations, potential delay settings, and potential gain settings have been considered, the modified and/or combined transfer functions, which may represent predicted transfer functions, are recorded for each listening position 922. Block 606 may contain fewer or additional steps not depicted in
15 Figure 9.

[0136] STATISTICAL ANALYSIS

20 **[0137]** Various statistical analyses may be performed to analyze the predicted transfer functions. Figure 10 is a table showing raw data for various listening positions (seats 1-5) for various frequencies (20-80 Hz in 2 Hz increments) and examples of statistical analyses that may be performed. As discussed previously, the raw data may be modified based on potential values of one or more parameters. For example, if potential values for correction include a filter with a center frequency at 30 Hz, a bandwidth of 10 Hz, and a level setting of -6 dB, the raw data for frequencies 26-34 may be adjusted accordingly to generate the predicted transfer function.

25 **[0138]** In a multiple listening position audio system, the statistical analyses may be based on any mathematical tool that evaluates the predicted transfer functions, such as taking the average, standard deviation, spatial standard deviation, spatial envelope, or spatial maximum average across the seats. For example, the spatial average at 20 Hz is -15.94 dB, which is calculated by averaging the amplitude readings at 20 Hz for seats 1 to 5. The spatial
30 variance at 20 Hz is -4.72 dB, which is calculated by taking the variance of the amplitude readings at 20 Hz for seats 1 to 5. The spatial standard deviation is 2.17 dB for 20 Hz and may be computed as the square root of the spatial variance. The spatial envelope may be the

difference between the highest and lowest readings. At 20 Hz, the highest and lowest readings are -12.99 dB and -18.13 dB, so that the spatial envelope is 5.14 dB. The spatial maximum minus average may be computed by selecting the maximum value and subtracting the average. For 20 Hz, the maximum value is -12.99 dB and the average is 15.94 dB, so that the spatial max – average is 2.96.

[0139] Based on the spatial averages, a mean overall level may be calculated. Other calculations may be based on the spatial averages, such as a variance of the spatial averages, the standard deviation of the spatial averages, the envelope of the spatial averages, and the maximum – average of the spatial averages. For example, in Figure 10, the maximum – average of the spatial average is 6.42 – (-8.97, the mean overall level) or 15.39. Likewise, the mean spatial variance, mean spatial standard deviation, mean spatial envelope, and mean spatial maximum – average may be calculated based on the spatial variances, spatial standard deviations, spatial envelopes, and spatial maximum - average, as shown in Figure 10.

[0140] An example equation is shown below for the mean spatial variance:

$$\text{Mean Spatial Variance} = \frac{\sum_{f=f_1}^{f_2} \text{var}_s(R(s, f))}{F} \quad (5)$$

where: $\text{var}_s(R(s, f))$ is the variance in the magnitude (in dB) of the transfer functions across all listening positions s , calculated at any one frequency f .

[0141] The statistical analyses may also be based on the average of the frequencies by seat, such as the mean level. For example, all of the frequencies at seat 1 may be averaged to calculate a mean level of -10.16 dB. The mean levels at each of the seats may be used to calculate a mean overall level, a variance of the mean levels, a standard deviation of the mean levels, an envelope of the mean levels, and a maximum – average of the mean levels, as shown in Figure 10.

[0142] Variance of the spatial average may be defined as:

$$\text{Variance of the Spatial Average} = \frac{\sum_{s=1}^S \text{var}_f(R(s, f))}{S} \quad (6)$$

where: $\text{var}(R_f(k))$ is the variance in the magnitude (in dB) of the transfer functions across all frequencies, calculated at any one listening position; and

S is the total number of listening positions.

[0143] Acoustic efficiency may quantify the total efficiency in terms of overall output versus number of active loudspeakers. Acoustic efficiency may be defined as:

$$\text{Acoustic Efficiency} = \frac{\sum_{f1}^{f2} \sum_s R(s, f)}{FS \sum_k a} \quad (7)$$

5 where: a are the amplitudes of the loudspeakers k in any given configuration.

[0144] The statistical analyses may measure different metrics or aspects of the predicted transfer functions. One type of statistical analysis may indicate consistency of the predicted transfer functions across the multiple listening positions. Examples of the first type, discussed above, include mean spatial variance, mean spatial standard deviation, mean spatial envelope (*i.e.*, min and max), and mean spatial maximum average, if the system is equalized. For example, a low value for the mean spatial variance indicates that the transfer functions tend to be consistent at each seat (*i.e.*, the values at the seats are close to the spatial average).

[0145] A second type of statistical analysis may measure how much equalization is necessary for the predicted transfer functions. Specifically, the second type of statistical analysis may be a measure of flatness. Examples of the second type include variance of spatial average, standard deviation of the spatial average, envelope of the spatial average, and variance of the spatial minimum. Examining the variance of the spatial average, this analysis provides a measure of consistency from seat-to-seat on average.

20 [0146] A third type of statistical analysis may measure the differences in overall sound pressure level (SPL) from seat to seat for the predicted transfer functions. Examples of the third type include variance of mean levels; standard deviation of mean levels, envelope of mean levels, and maximum average of mean levels.

[0147] A fourth type of statistical analysis may examine the efficiency of the predicted transfer functions at the single listening position or the multiple listening positions. In effect, the statistical analysis may be a measure of the efficiency of the sound system for a particular frequency, frequencies, or range of frequencies at the single listening position or at the multiple listening positions. An example of the fourth type includes acoustic efficiency. The acoustic efficiency may measure the mean overall level divided by the total drive level for each loudspeaker. Acoustic efficiencies for the predicted transfer functions may be

examined, and the parameter or parameters for the predicted transfer function with a higher or the highest acoustic efficiency may be selected.

[0148] A fifth type of statistical analysis may examine output of predicted transfer functions at the single listening position or the multiple listening positions. The statistical analysis may be a measure of the raw output of the sound system for a particular frequency, frequencies, or range of frequencies. For a single listening position system, an example of a statistical analysis examining output includes mean level. For a multiple listening position system, an example of a statistical analysis examining output includes mean overall level. The mean overall level may indicate how loud an audio system can play at a certain listening position or multiple listening positions. A sixth type of statistical analysis examines flatness of predicted transfer functions at a single listening position. The statistical analysis may analyze variance of the predicted transfer functions at the single listening position, such as amplitude variance and amplitude standard deviation.

[0149] Any of the statistical analyses may be band limited. For example, the mean overall level may be measured over a particular frequency band, such as frequencies under 40 Hz, to determine the amount of output at a certain frequency or set of frequencies. Typically, the maximum output of a subwoofer is limited below 40 Hz compared to frequencies above 40 Hz. Therefore, it may be advantageous to optimize the mean overall level below 40 Hz. Potential parameters that generate the highest or higher mean overall output at the listening positions in the 20 - 40 Hz range may then be used in the audio system. Likewise, in a single position audio system, it may be advantageous to optimize for mean level below 40 Hz.

[0150] As discussed above, various statistical analyses may be performed. Figure 11 is one example of an expanded block diagram of block 608 from Figure 6 depicting statistical analyses for acoustic efficiency and mean spatial variance. The program executing in computational device 570 shown in Figure 5 may perform this comparison. Transfer functions may be compared across the listening positions as a function of frequency to give a spatial average, as shown in block 1102. For example, predicted transfer functions may be compared as a function of frequency.

[0151] The spatial average, which may comprise a mean position amplitude, may be viewed as numerically describing the acoustic output from one or a combination of loudspeaker locations perceived at multiple listening positions, such as 450-455 of Figure 4. The spatial average may be determined by comparing, as a function of frequency, the

amplitude components of the modified or unmodified transfer function from a single loudspeaker location across the positions or by comparing the modified or unmodified combined transfer functions from a plurality of loudspeaker locations across the positions. While any method may be used to perform the comparison, one method is to average the dB values of the amplitude components from all the listening positions to give a spatial average for each frequency, as shown in Figure 10. How the amplitude components for each listening position vary from the spatial average may be expressed as a variance, such as a position variance. Thus, if amplitude values of 4 dB and 2 dB are compared by averaging to give the spatial average of the amplitude of 3 dB, the spatial variance value could be 2.

[0152] As discussed in Figure 10, variability between the amplitude values may be expressed as sample variance, standard deviation (STD), spatial envelope, spatial maximum – average or by any other method of expressing the variability between numerical values. For example, if the 60 Hz transfer function for a loudspeaker at location 440 is +1 dB at position 450, +1 dB at position 451, -2 dB at position 452, +2 dB at position 453, +3 dB at position 454, and +3 dB at position 455, the spatial average amplitude would be +1.33 dB with a spatial variance of 3.47.

[0153] The spatial average and the spatial variances may be recorded, as shown in block 1104. The program executing in computational device 570 may determine the frequency having the largest spatial variance across all the listening positions for each potential loudspeaker location and each combination of potential loudspeaker locations, as shown at block 1106. This frequency may be used as the center frequency to apply equalization. Multiple center frequencies may also be determined, such as the three center frequencies having the largest spatial variances, if multiple equalizations are implemented.

[0154] The program executed in computational device 570 may then modify the amplitudes of the determined center frequency with the equalization bandwidth and level settings selected in block 716, as shown in block 1108. Thus, the numerical amplitude components for specific frequencies may be increased or reduced for a selected bandwidth of the determined (or selected if equalization modifications were performed before combination 912) frequency. For example, a 12 dB reduction in amplitude could be applied at 60 Hz with a $Q = 4$. Unlike frequency-independent gain settings, the numerical amplitude component at different frequencies may be modified by different equalization level settings. In this

manner, one of a plurality of equalization settings may be applied to the spatial average for one or a combination of potential loudspeaker locations.

[0155] The modified spatial averages may be recorded, as shown in block 1110. If additional equalizations settings were selected in 716, blocks 1108 through 1110 may be repeated, as shown in block 1112. When the spatial averages have been modified with all selected equalization settings, the modified or unmodified spatial averages may be compared, as shown in block 1114. The program executed in computational device 570 may perform this comparison.

[0156] All spatial averages may be compared to provide a solution that includes an acoustic efficiency and a mean spatial variance for each potential loudspeaker location and each combination of potential loudspeaker locations with the selected corrections for all the listening positions, as shown in block 1114. Figure 10 provides examples of the mean overall level, which may be used to determine the acoustic efficiency, and the mean spatial variance.

[0157] As discussed previously, the determined acoustic efficiency numerically describes the ability of a given sound system to generate higher sound levels at one or more listening positions from the same power input if the solution is implemented. Thus, acoustic efficiency is the ratio of the sound pressure level at one or more listening positions to the total low-frequency electrical input of the sound system. For example, the acoustic efficiency may comprise the mean overall level divided by the total drive for all active loudspeakers. The determined spatial variance numerically describes the similarity of the low-frequency acoustic signal perceived at each listening position if the solution is implemented.

[0158] Figure 12 is another example of an expanded block diagram of block 608 from Figure 6 depicting statistical analyses for acoustic efficiency and variance of the spatial average. Amplitude responses may be compared across the frequencies as a function of listening position to generate a mean level at each listening position, as shown in block 1202. Figure 10 shows one example of calculating the mean level, where the amplitudes for a set of frequencies at a listening position are averaged to produce the mean overall level. Specifically, the mean level may be calculated for seat 1 shown in Figure 1 by averaging the amplitudes for frequencies 20 through 80. The mean levels may be averaged to calculate the mean overall level, as shown in Figure 10. Further, the mean levels may be analyzed to determine the variance of mean levels, standard deviation of mean levels, envelope of mean levels and maximum – average of mean levels, as shown in Figure 10. In addition to the

mean level, an amplitude variance or an amplitude standard deviation may be calculated. The amplitude variance may comprise variations of the amplitudes for a specific listening position. As one example shown in Figure 10, the amplitude variance may comprise calculating the variance of the amplitude values for seat 1 (-177.71, -16.60 . . . -5.65). The
5 amplitude variance may be a measure of smoothness of the transfer function (either predicted or unmodified transfer functions) for a specific listening position. In a multiple listening position audio system, the amplitude variances for each listening position may be averaged to determine a mean amplitude variance. In a single listening position audio system, the amplitude variance or amplitude standard deviation may be used to statistically evaluate the
10 predicted configuration.

[0159] The recorded mean levels may be averaged to determine the mean overall level, as shown at block 1204. The mean overall level may be used to calculate the acoustic efficiency, as shown at block 1206. The acoustic efficiency may be determined by dividing the mean overall level by the total drive level for each loudspeaker. Acoustic efficiency
15 numerically describes the ability of a given sound system to generate higher sound levels, such as low-frequency sound levels if the analysis is band limited, at one or more listening positions from the same power input. The variance of the spatial average may be calculated by first calculating the spatial averages across the listening positions, and calculating the variance of the spatial averages, as shown at block 1208. The determined variance of the
20 spatial average numerically describes how closely the amplitude values will correspond to the target value if the solution is implemented. The acoustic efficiency and/or the variance of the spatial average may be used to compare the predicted transfer functions, as shown at block 1210.

[0160] Figure 13 is a table of potential configurations for an audio system, where the
25 potential configurations are ranked by mean spatial variance (MSV). The potential configurations include values corresponding to various combinations of the audio system parameters of loudspeaker location, loudspeaker number, and correction settings that include gain, delay, and equalization. The first four configurations and another configuration (such as solution 10,000) are shown. Further, Figure 14 provides values for acoustic efficiency
30 (AE), and variance of the spatial average (VSA) for illustrative purposes. Other types of statistical analyses may be used.

[0161] For the potential configurations in Figure 13, six listening positions, a minimum of two loudspeakers, a maximum of three loudspeakers, and four potential loudspeaker locations are considered. Three possible gain settings of 0 dB, -6 dB, and -12 dB are considered. Delay settings of 0 ms, 5 ms, and 10 ms are considered. The center
5 frequency for implementation of parametric equalization may comprise the frequency having the maximum variance, as determined at block 1106 of Figure 11. Bandwidth settings of 1, 4, and 16 are considered. Equalization level settings of 0 dB, -6 dB, and -12 dB are considered.

[0162] The methodology may recommend at least one of the potential configurations
10 based on the statistical analysis. The recommendation may be based on one or more statistical analysis. As shown in Figure 13, the potential configurations are ranked based on mean spatial variance (MSV). Alternatively, the solutions may be ranked based on acoustic efficiency (AE) and/or variance of the spatial average (VSA). Or, the solutions may be based on a plurality of statistical analyses, such as ranking based on a weighting of various
15 statistical analyses. For example, different weights may be assigned to mean spatial variance, acoustic efficiency and/or variance of the spatial average.

[0163] From the illustrative solutions presented in Figure 13, the user or the program executing in computational device 570 may manually select a solution for the parameters in response to the statistical analysis. Figure 13 illustrates that Solution 1 has the least mean
20 spatial variance, meaning that the implementation of a loudspeaker at potential locations 1 and 2 with the depicted correction settings for each system parameter will result in the low-frequency signal heard by each listener being the most similar. Solution 5 results in acoustic efficiency being the greatest; however, the mean spatial variance is higher when compared to the other solutions. Thus, a user may wish to implement Solution 2, which has neither the
25 lowest mean spatial variance nor the greatest acoustic efficiency, but results in a good balance when both are considered. Solution 3 results in the least variance of the spatial average at each listening position, but has higher mean spatial variance and lower acoustic efficiency when compared with Solution 2. Thus, Solution 2 may again be the desired choice when variance of the spatial average is considered because it has a good combination of
30 spatial variance, acoustic efficiency, and variance of the spatial average.

[0164] While a particular solution simultaneously may improve acoustic efficiency, mean spatial variance, and variance of the spatial average, depending on the room and the

sound system, a trade-off may be required. The user may review the ranked results and implement the values corresponding to the selected solution to provide the desired combination of low-frequency improvement. For example, the user may determine if some acoustic efficiency should be traded for less spatial variance or vice versa.

5 **[0165]** In addition to the user, the program executing in computational device 570 may select a solution to implement in the sound system by weighing the solutions from the statistical analysis. Specifically, if the solution resulting in the least mean spatial variance significantly decreases acoustic efficiency, the program may select the desired solution based on weighting factors selected by the user. For example, a user may want increases in acoustic
10 efficiency to be twice as important as decreases in mean spatial variance. Thus, the program executing in computational device 570 may select a solution based on user-preferred weightings if a trade-off in low frequency performance is involved. As discussed above, other types of statistical analysis may be used in evaluating a potential configuration. For example, amplitude variance or mean amplitude variance may be used to evaluate potential
15 configurations.

[0166] The S column in Figure 13 shows the number of loudspeakers and the location for each loudspeaker in relation to the four potential locations. Each solution provides values corresponding to the potential location where a loudspeaker should be placed to implement that solution. Similarly, the number of loudspeakers required to implement the solution is
20 also provided. For example, for Solution 1, two loudspeakers are placed at potential locations 1 and 2. For solution 5, three loudspeakers are placed at positions 1, 3, and 4.

[0167] In this manner, the solutions may illustrate the effect of using fewer or greater number of loudspeakers. Specifically, the solutions may illustrate that it is not beneficial, or even detrimental, in using more loudspeakers (*e.g.*, selecting three verses two loudspeakers
25 does not effect low frequency sound performance, or degrade low frequency sound performance at the selected listening positions). The solutions also allow the user to weigh the cost of additional loudspeakers and corrections relative to the potential improvement in low-frequency performance. For example, adding parametric equalization to one of a pair of loudspeakers may improve spatial variance to a greater extent than adding two additional
30 loudspeakers.

[0168] The Gain column in Figure 13 illustrates the gain setting to implement at each loudspeaker to generate the desired increase in low-frequency performance. As previously

mentioned, the statistical analysis may independently determine gain settings for implementation at each potential loudspeaker location. For example, in Solution 3, a 6 dB decrease in gain is implemented for the loudspeaker at potential location 2 while a gain correction is not implemented for the loudspeaker placed at potential location 3.

5 **[0169]** Generally accepted acoustic theory predicts that two loudspeakers having identical positioning from opposing, perpendicular room boundaries must have equal gain settings to cancel room modes to improve low-frequency performance. While this may be true if loudspeaker placement is exact, the room is symmetrical, and the room boundaries have identical acoustic character, the acoustic character of room boundaries is generally quite
10 varied. Thus, the statistical analysis may determine solutions having gain setting values that provide increased low-frequency performance when the loudspeakers are not identically spaced from the room boundaries. Solutions also may be provided having gain setting values that provide increased low-frequency performance when the room boundaries have varied acoustic character, are not perpendicular to each other, and have openings, such as doors.

15 **[0170]** The statistical analyses also may determine solutions that decrease the gain setting at a potential loudspeaker location to increase the low-frequency sound level heard at one or more listening positions. This can be seen by comparing Solution 1 with Solution 3, where Solution 3 shows that a 6 dB gain reduction for loudspeaker 2 provides a greater acoustic efficiency than obtained from Solution 1 - where both loudspeakers have a unity
20 gain of 0. This is counterintuitive to generally accepted acoustic theory, where it is expected that turning down the volume will reduce the sound level.

[0171] The Delay column in Figure 13 shows the delay setting to implement at each loudspeaker for each solution. As previously mentioned, the statistical analysis may independently determine delay settings for implementation at each potential loudspeaker
25 location. Thus, for Solution 3, a 10 ms delay is implemented for the loudspeaker at potential location 2 while delay is not implemented for the loudspeaker placed at potential location 3. Delay settings also may have a beneficial effect on acoustic efficiency.

[0172] The Center, Bandwidth, and Level columns in Figure 13 provide the parametric equalization settings to implement at each loudspeaker for each solution. As
30 previously mentioned, various types of equalization may be investigated including parametric, graphic, paragraphic, shelving, FIR, and transversal. The statistical analysis may independently determine equalization settings for implementation at each potential

loudspeaker location. In parametric equalization, center frequency determines the frequency at which the adjustment will be applied, for example 60 Hz. Bandwidth determines how broad the amplitude adjustment will be. For example, if $Q = 4$, the bandwidth = 15 Hz. Level determines the amount of amplitude adjustment that will be applied, such as -12 dB.

5 While an amplitude increase or decrease may be applied, generally a decrease in amplitude is applied. Thus, for Solution 3, a 6 dB reduction in level is applied over a Q of 16 at a center frequency of 27 Hz for the loudspeaker at potential location 2 and a 0 dB reduction in level is applied over a Q of 1 at a center frequency of 41 Hz for the loudspeaker at potential location 3. Because frequency-dependent gain (equalization level) is another type of gain reduction,
10 reducing the equalization level setting at one or at a plurality of frequencies on one or a plurality of loudspeakers may also increase the acoustic efficiency of low-frequencies produced at one or more seating positions.

[0173] Of note, acoustic efficiency and mean overall level in a particular frequency band (such as frequencies below 50 Hz) may increase by decreasing frequency-independent
15 or dependent gain and/or delay. For example, the acoustic efficiency and mean overall level may be increased by decreasing the volume at one or more loudspeakers. This increase in acoustic efficiency and mean overall level may arise because amplitude peaks generally cover a larger physical volume of the room than amplitude dips. For example, a peak may cover two to three listening positions while a dip may only cover one listening position. When the
20 statistical analysis determines solutions providing reduced mean spatial variance and/or variance of spatial average, the implementation of the solution values into the sound system may provide for an increase in peaks (constructive interference) at the expense of dips (destructive interference) in the amplitude response. This increase in peaks in relation to dips at the listening positions may be attributable to a reduction in destructive interference
25 between the sound waves of the acoustic signal. Thus, it may be possible to realize an increase in low-frequency acoustic efficiency because acoustic energy may be heard that was attenuated by wave cancellation before the corrections were implemented.

[0174] Figure 14 is an expanded block diagram of block 612 from Figure 6 depicting the implementation of the values corresponding to the selected solution in the sound system.
30 The solution values corresponding to loudspeaker number and location are implemented by positioning one or more loudspeakers at the determined location or locations, as shown at block 1402. Thus, to implement Solution 2 from Figure 13, a loudspeaker would be placed at

potential locations 1, 2, and 3. Similarly, to implement Solution 1 having the least spatial variance, loudspeakers would be placed at potential locations 1 and 2.

[0175] Correction settings may be implemented in the sound system 500 in the analog domain (*e.g.*, gain or equalization) or the digital domain (*e.g.*, gain, equalization, or delay) and at any convenient point in the signal path. Gain settings may be implemented in the sound system 500 by independently lowering or raising a gain adjustment (commonly referred to as loudness or volume control) at each loudspeaker, as shown at block 1404. Thus, to implement Solution 2 from Figure 14, the gain for the loudspeaker at potential location 1 would be reduced by 6 dB from unity, the gain of the loudspeaker at potential location 2 would remain at unity or 0, and the gain of the loudspeaker at potential location 3 would be reduced 12 dB from unity. While gain corrections are generally implemented by attenuating or increasing the electrical signal that the transducer converts to an acoustic signal, they may also be implemented by placing multiple loudspeakers that respond to a common electrical signal at a single location, and the like. Or, the correction settings may be implemented by changing the wiring of the loudspeakers.

[0176] Delay settings, such as 10 milliseconds (ms), may be implemented in the sound system 500 in the digital domain at each loudspeaker, as shown at block 1406. The delay setting may be implemented after a surround sound or other processor generates a low-frequency output from an input. For example, if a digital DOLBY DIGITAL 5.1[®] or DTS[®] signal is input to a digital surround sound decoder, a LFE (low-frequency effects) signal is output. Prior to converting this output to the analog domain for amplification, delay settings may be introduced. The delay settings may be implemented in the processor 504, which can then output analog signals, or at the loudspeaker, if the loudspeaker electronics can accept a digital input. Thus, to implement Solution 2 from Figure 13, a delay of 0 ms (no delay) would be applied for the loudspeaker at potential location 1, a delay of 10 ms would be applied to the signal reproduced by loudspeaker at potential location 2, and no delay would be applied for loudspeaker at potential location 3.

[0177] Equalization settings may be implemented in the sound system 500 by independently applying equalization at each loudspeaker, as shown at block 1408. Parametric equalization is a convenient method of implementing equalization at each loudspeaker. Parametric equalization allows for the implementation of settings to select the center frequency, the bandwidth, and the amount of amplitude increase or decrease (level) to

apply. A center frequency, bandwidth, and level setting may be independently applied to the signal reproduced by each loudspeaker. Thus, to implement Solution 2 from Figure 14, the center frequency, Q, and level settings would be set to 22 Hz, 1, and -6 dB for loudspeaker 1; and 85 Hz, 1, and -12 dB for loudspeaker 3. Equalization would not be implemented for the loudspeaker at potential location 2 because the level setting is 0 dB or unity. Block 612 may contain fewer or additional steps not depicted in Figure 14.

[0178] EXAMPLES

[0179] Five home theater systems were examined using the above-referenced analysis. Of the five systems, three were actual existing home theater systems and two were experimental systems in listening rooms. In each example, the optimized system is compared to a relevant base line. Further, in each example, the results are predicted using real measured data.

[0180] Example 1

[0181] The first system investigated is not a dedicated home theater. Therefore, the existing subwoofer locations are a compromise between low frequency performance and aesthetic concerns. Figure 15 is the layout for the room in Example 1, the scale of which is approximately 100:1. The square boxes represent the two subwoofer locations and the circles represent the three listening positions. The room depicted in Figure 15 is approximately 27' x 13', with a 45° angle for one of the walls, and has a 9' ceiling. The walls and ceiling are constructed of drywall and 2" x 6" studs. The floor is constructed of a concrete slab and is covered with ceramic tile. An area rug covers a large portion of the floor.

[0182] Figure 16 describes the low frequency performance of the system before low-frequency analysis was applied. The heavy solid curve in the middle of Figure 16 is the average amplitude response for the three listening positions. The lighter middle curves are the responses at each listening position and the upper dashed curve is the mean spatial variance as a function of frequency, raised by 10 dB for clarity. The text in the bottom left lists the metrics for this configuration, with a mean spatial variance of 21.4173 dB, a variance of the spatial average of 23.6992 dB, and an acoustic efficiency of -12.6886 dB. The text in the bottom right of Figure 16 shows the parameters for the configuration, with no modification to the correction factors. Figure 17 is a graph for the predicted performance after low-frequency analysis is applied. Table 1 compares the performance and parameters of the system before and after low-frequency analysis.

Active Subwoofers	Low-frequency analysis (yes/no)	Mean Spatial Variance	Variance of the spatial average	Acoustic Efficiency
1, 2	No	21.4 dB	23.7 dB	-12.7 dB
1, 2	Yes	7.4 dB	12.0 dB	-12.3 dB

Table 1

[0183] Example 1, which has one wall with a 45° angle, shows that the low-frequency analysis may be applied to any room configuration, such as a non-rectangular room. Further, the system in Example 1 has the number and positions of subwoofers predetermined. The low-frequency analysis in Example 1 focuses on correction factors to improve the low-frequency response of the system. For example, correction factors directed to gain, delay, and equalization are applied to at least some of the loudspeakers in Example 1. The results of the low-frequency analysis, as shown in Figures 16 and 17 and Table 1 show that with the analysis, the mean spatial variance and variance of the spatial average have decreased dramatically, which is beneficial, and the acoustic efficiency has increased slightly, which is also beneficial.

[0184] Example 2

[0185] The second system investigated in Example 2 is a \$300,000+ dedicated home theater. Figure 18 describes the layout of the room in Example 2. The system features one subwoofer in each corner of the room, a front-projection video system and a riser for the second row of seating. The room is approximately 26' x 17' and has a 9' ceiling. Two of the walls are constructed of concrete blocks and two of the walls are constructed from drywall and 2" x 4" studs. The floor is a carpeted concrete slab. The second row of seating is on an 8" riser constructed of plywood and 2" x 4" studs. The room features extensive damping on all walls. Figures 19 and 20 define the low frequency performance before and after low-frequency analysis. Table 2 compares the performance of the system in Example 2 before and after low-frequency analysis.

Active Subwoofers	Low-frequency analysis (yes/no)	Mean Spatial Variance	Variance of the spatial average	Acoustic Efficiency
1, 2, 3, 4	No	5.1 dB	21.3 dB	-17.3 dB
1, 2, 3, 4	Yes	2.1 dB	17.4 dB	-18.0 dB

Table 2

[0186] The system in Example 2 has the number and positions of subwoofers predetermined with four subwoofers in each corner of the room. The low-frequency analysis focuses on correction factors to improve the low-frequency response of the system. For example, correction factors directed to gain, delay, and equalization are applied to at least some of the loudspeakers in Example 2. The results of the low-frequency analysis, as shown in Figures 19 and 20 and Table 2 show that with the analysis, the mean spatial variance and variance of the spatial average have improved, and the acoustic efficiency has decreased slightly.

[0187] Example 3

[0188] The third system in Example 3 comprises a home theater set-up in a family room. Figure 21 shows the layout of the room in Example 3. The room is approximately 22' x 21' and features a sloped ceiling. The walls and ceiling are constructed of drywall and 2" x 4" studs. The floor is a concrete slab with the perimeter covered by tile and the central area carpeted. The left side wall features several windows which can be (and were) covered by heavy drapes. The system originally featured two subwoofers in the front of the room. Figure 22 describes the low frequency performance in the original configuration before low-frequency analysis was applied, with the system constrained to using subwoofers 1 and 2 in the front of the room. Figure 23 describes the low frequency performance after low-frequency analysis was applied, with the system constrained to using subwoofers 1 and 2. Two additional subwoofers were placed in the back of the room and low-frequency analysis was applied, the results of which are presented in Figure 24. Table 3 compares the performance of the system before and after the improvements were made.

Active Subwoofers	Low-frequency analysis (yes/no)	Mean Spatial Variance	Variance of the spatial average	Acoustic Efficiency
1, 2	No	23.6 dB	37.2 dB	-4.8 dB
1, 2	Yes	14.7 dB	34.3 dB	-7.0 dB
1, 2, 3, 4	Yes	5.7 dB	11.2 dB	-2.5 dB

Table 3

[0189] Example 3 highlights potentially different solutions based on the number of subwoofers, placement of subwoofers, and correction factors applied. Figure 23 provides a solution for subwoofers that are placed in the same configuration as shown in Figure 22. Using low-frequency analysis, Figure 23 illustrates that with the same configuration, the

mean spatial variance decreases dramatically, the variance of the spatial average decreases, and the acoustic efficiency decreases. Figure 24 provides a solution for subwoofers that are placed in each corner of the room. Using the low-frequency analysis, Figure 24 shows that the mean spatial variance, variance of the spatial average, and acoustic efficiency are significantly improved.

[0190] Example 4

[0191] The system in Example 4 is in a room that is open to an adjacent room. Figure 25 is the layout of the room in Example 4. The main room is 20' x 15' and is open to another room that measures 17' x 13'. Both rooms have an 8' "dropped ceiling" and a slab concrete floor covered by carpet. All of the walls are constructed from drywall and 2" x 4" studs. The original configuration used one subwoofer. Figure 26 is a graph for the performance of the system in the original configuration. It should be noted that this is an exceptionally good listening room as evidenced by the graph in Figure 26. Six potential subwoofer locations were measured and low-frequency analysis was used to determine the best four. Figure 27 is a graph for the performance of the system after low-frequency analysis chose the best four subwoofer locations (subwoofers 1, 2, 4, and 5) and optimized each subwoofer's parameters. Table 4 compares the set-up before and after optimization.

Active Subwoofers	Low-frequency analysis (yes/no)	Mean Spatial Variance	Variance of the spatial average	Acoustic Efficiency
1	No	2.0 dB	50.5 dB	5.3 dB
1, 2, 4, 5	Yes	0.4 dB	51.5 dB	1.1 dB

Table 4

[0192] Example 4, similar to Example 3, highlights potentially different solutions based on different aspects of the sound system such as the number of subwoofers, placement of subwoofers, and correction factors applied. Through low-frequency analysis, the number of the subwoofers, the placement of the subwoofers from the potential subwoofer locations, and/or the correction factors may be determined. Specifically, up to six potential subwoofers could have been included in the system in Example 4. Low-frequency analysis determined that four subwoofers were the optimal number. Further, six potential subwoofer locations were available, with positions 1, 2, 4, and 5 selected. Using low-frequency analysis, Figure 27 shows that the mean spatial variance decreases, the variance of the spatial average increases, and the acoustic efficiency increases.

[0193] Example 5

[0194] The room in Example 5 is an engineering listening room. Figure 28 shows the layout of the engineering listening room for Example 5. The room is approximately 21' x 24' and has a 9' ceiling. The walls and the ceiling are constructed with two layers of drywall and 2" x 6" studs. The floor is a concrete slab with wall-to-wall carpeting. Because all the room boundaries are relatively stiff, this room has little damping at low frequencies. In this regard, the room in Example 5 has very different acoustical properties from the room in Example 2, which had significant damping at low frequencies.

[0195] A total of 8 potential subwoofer locations and 5 listening positions were measured to yield 40 transfer functions. Several configurations were then simulated, as detailed in Figures 29-39. All of the results in this example are predicted using the real measured data from the 40 transfer functions.

[0196] Figure 29 is a graph for the low frequency performance for the common scenario of a single subwoofer in a front corner (subwoofer 1 in Figure 28). This is compared to a single best subwoofer configuration found by low-frequency analysis in Figure 30. Figure 31 is a graph for the low frequency performance for the common "stereo subwoofer" configuration using subwoofers 1 and 3. Figure 32 is a graph for the performance of a two subwoofer system using low-frequency analysis where the low-frequency analysis is constrained to finding the best solution for a pair of subwoofers. As shown in Figure 32, the best pair solution uses subwoofers 6 and 7 shown in Figure 28.

[0197] Figure 33 is a graph for the low frequency performance for a four-corner configuration using subwoofers 1, 3, 5, and 7. Figure 34 is a graph for the performance of the same four subwoofers once low-frequency analysis has been applied. Figure 35 is a graph for the low frequency performance for a four-midpoint configuration using subwoofers 2, 4, 6, and 8. Figure 36 is a graph for the low frequency performance of the same four subwoofers once low frequency analysis has been applied.

[0198] Figure 37 is a graph for the low frequency performance of a four-subwoofer "optimum" configuration. The "optimum" configuration is based on ranking results of the analysis using Spatial Variance as the sole ranking factor. As shown in Figure 37, the "optimum" four-subwoofer configuration includes subwoofers placed at positions 2, 5, 6, and 7. Further, the "optimum" configuration shown in Figure 37 includes correction factors for each of the subwoofers. Similarly, Figures 38 and 39 show the low frequency performance

of other four-subwoofer “optimum” configurations. The “optimum” configurations in Figures 38 and 39 are based on ranking results of the analysis using mean spatial variance and variance of the spatial average, and mean spatial variance and acoustic efficiency, respectively.

5 [0199] Figure 40 shows the mean spatial variance for all the simulated configurations investigated for the engineering room in Example 5. The points in Figure 40 where the typical “stereo subwoofer” and “four corner” configurations fall on the plot have been highlighted.

[0200] Table 5 compares the low frequency performance of all the configurations
10 simulated in Example 5.

Active Subwoofers	Low-frequency analysis (yes/no)	Mean Spatial Variance	Variance of the spatial average	Acoustic Efficiency
1	No	25.9dB	52.4dB	-7.9dB
7	Yes	15.9dB	40.25 dB	-6.6dB
1,3	No	25.2dB	62.8 dB	-10.4dB
6,7	Yes	5.9dB	46.0dB	-11.0dB
1,3,5,7	No	20.3dB	57.4dB	-13.1dB
1,3,5,7	Yes	6.7dB	34.0dB	-12.1dB
2,4,6,8	No	17.9dB	58.4dB	-18.0dB
2,4,6,8	Yes	6.2dB	57.1dB	-17.1dB
2,5,6,7	Yes	3.6dB	26.2dB	-14.2dB
1,5,6,7	Yes	4.6dB	18.3dB	-13.5dB
1,5,6,7	Yes	4.6dB	49.0dB	-11.9dB

Table 5

[0201] Examining the results in Table 5, low-frequency analysis may improve the low-frequency performance of the sound system when using the parameters of position of the subwoofers and/or correction factors. Comparing Figures 29 and 30, which constrains the
15 number of subwoofers to one, low frequency performance was improved using low-frequency analysis. The analysis suggested a location for the subwoofer (location 7), resulting in decreasing the mean spatial variance and the variance of the spatial average, and increasing the acoustic efficiency.

[0202] Comparing Figures 31 and 32, which constrains the number of subwoofers to
20 two, low frequency performance was again improved using low-frequency analysis. The analysis suggested locations for the subwoofers (locations 6 and 7) and correction factors,

resulting in decreasing the mean spatial variance and the variance of the spatial average, and a slight decrease in the acoustic efficiency.

[0203] Comparing Figures 33 and 34, which constrains the number and the position of the subwoofers (*i.e.*, a subwoofer in each corner of the room), the low-frequency performance was improved using the low-frequency analysis. The analysis suggested correction factors, resulting in decreasing the mean spatial variance and variance of the spatial average, and increasing the acoustic efficiency. Comparing Figures 35 and 36, which constrains the number and the position of the subwoofers (*i.e.*, a subwoofer in the four-midpoints of the room), the low-frequency performance was improved using the low-frequency analysis. The analysis suggested correction factors, resulting in decreasing the mean spatial variance and variance of the spatial average, and increasing the acoustic efficiency.

[0204] There are several criteria by which to rank solutions generated by the low-frequency analysis. Ranking may be based on spatial variance, variance of the spatial average, acoustic efficiency, or any combination thereof. Figures 36-38, each of which constrain the number of subwoofers to four, illustrate examples of selecting positions for the subwoofers and correction factors based on various types of ranking criteria. Figure 36 ranks the solutions solely based on spatial variance, so that its preferred solution has the lowest spatial variance. Figure 37 ranks the solutions based on a combination of spatial variance and variance of the spatial average, so that its preferred solution selects different subwoofer locations, has a higher spatial variance, and has a lower variance of the spatial average than the preferred solution in Figure 36. Figure 38 ranks the solutions based on a combination of spatial variance and acoustic efficiency, so that its preferred solution selects different subwoofer locations, has a higher spatial variance, and has a higher acoustic efficiency than the preferred solution in Figure 36.

[0205] Figure 41 shows the predicted low frequency performance of a typical four-corner subwoofer configuration using low-frequency analysis, focusing on optimizing amplitude and delay correction factors. Figure 42 is the actual low frequency performance after optimization. Comparing Figures 41 and 42, agreement between the predicated and actual performance below 70Hz is excellent. Thus, there is substantial agreement between performance predicted by low-frequency analysis and actual performance.

[0206] In each of the above examples, spatial variance was significantly improved using the low-frequency analysis. The improvement in spatial variance ranged from a factor of 1.5 to 5. The improvement in spatial variance was usually accompanied by an improvement in variance of the spatial average and acoustic efficiency. One way to understand this is to examine the difference between peaks and dips in the modal response of rooms. Dips tend to be more location dependent than peaks. This means that dips will tend to cause more seat-to-seat variation and higher spatial variance than the spatially broader peaks. Thus, optimum solutions tend to be free of dips, which in turn improves variance of the spatial average and the efficiency factor.

[0207] Low-frequency analysis may work well with a variety of subwoofer systems, including those having two and four subwoofers. Low-frequency analysis may improve the performance with predetermined subwoofer locations and predetermined subwoofer number (e.g., a home theater system that has already been set-up such as those in Examples 1 and 2). Low-frequency analysis may generally perform better when it is free to choose the subwoofer locations, subwoofer number, and/or corrections, such as was discussed in Example 5.

[0208] Low-frequency analysis may focus on adjusting one, some, or all of the parameters discussed above including position of subwoofers, number of subwoofers, type of subwoofers, correction factors, or any combination thereof. Further, low-frequency analysis may focus on adjusting one, some, or all of the correction factors such as adjusting gain, delay and filtering simultaneously. However, all three correction factors do not need to be optimized to improve system performance. Finally, the analysis focuses on low-frequency performance; however, any frequency range may be optimized.

[0209] The flow charts described in Figures 4-12 and Figure 14 may be performed by hardware or software. If the process is performed by software, the software may reside in any one of, or a combination of, the hard disk, external disk 548, ROM 530 or RAM 524 in measurement device 520 or a hard disk, external disk, ROM, or RAM in computational device 570. The software may include an ordered listing of executable instructions for implementing logical functions (i.e., "logic" that may be implemented either in digital form such as digital circuitry or source code or in analog form such as analog circuitry or an analog source such as an analog electrical, sound or video signal), may selectively be embodied in any computer-readable (or signal-bearing) medium for use by or in connection with an instruction execution system, apparatus, or device, such as a computer-based system, processor-

containing system, or other system that may selectively fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions. In the context of this document, a "computer-readable medium," "machine-readable medium," "propagated-signal" medium, and/or "signal-bearing medium" is any means that may contain, store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device. The machine-readable medium may selectively be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. A non-exhaustive list of the machine-readable medium may include the following: an electrical connection "electronic" having one or more wires, a portable computer diskette (magnetic), a RAM (electronic), a ROM (electronic), an erasable programmable read-only memory (EPROM or Flash memory) (electronic), an optical fiber (optical), and a portable compact disc read-only memory "CDROM" (optical). The machine-readable medium may also comprise paper or another suitable medium upon which the program is printed, as the program may be electronically captured, via for instance optical scanning of the paper or other medium, then compiled, interpreted or otherwise processed in a suitable manner if necessary, and then stored in a computer and/or machine memory.

[0210] While various embodiments of the invention have been described, it will be apparent to those of ordinary skill in the art that many more embodiments and implementations are possible within the scope of the invention. Accordingly, the invention is not to be restricted except in light of the attached claims and their equivalents.